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THE PROPER SELECTION OF ENGINE CYCLES

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This report has been reviewed and is approved for publication.

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Some recent airplanes have failed to achieve design performance goals due to poor evaluation and accounting of installation losses which resulted in improper engine cycle selection.

Political constraints on the integration problem are discussed with particular reference to USAF and Industry Organizational Structures, shifting political atmospheres, and contractual competition. A recent airplane system

development is reviewed stressing the interrelationship of the engine and airframe manufacturers. Discussions of thrust-drag accounting and wind tunnel test techniques lead to a better understanding of uncertainties which exist in data generated in development programs. A methodology for utilizing sensitivity studies to reduce the potential effect of these uncertainties on cycle selection leads to discussions of flexible engine cycles and recommendations for time phasing future development programs. General conclusions and recommendations are provided. The report examines some problems of concurrent airframe-engine matching and defines a methodology for proper selection of engine cycle.

FOREWORD

This report was prepared in the Performance Branch (TBA), Turbine Engine Division, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, under Project 3066, "Gas Turbine Technology," Task 30661108.

The report represents a summation of the methodology and experience gained under the Exhaust System Interaction Program, United States Air Force Contracts F33615-70-C-1449 and F33615-70-C-1450. This work was conducted in the time period from April 1970 to June 1973.

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INTRODUCTION

Engine-airframe integration is a complex problem which only recently has begun to receive the attention which its importance merits. In the past, traditional development methods and contractual aspects of system procurement have placed the emphasis on component performance rather than system performance. The present cost-effective atmosphere of the weapons system acquisition process makes it imperative that a methodology of engine-airframe integration be developed which strikes the proper balance between system performance and component performance.

The present work proposes the nucleus of an engine airframe integration methodology evolved at the Air Force Aero Propulsion Laboratory, drawing on a considerable number of past integration efforts, both successful and unsuccessful. Only the nucleus is presented so as to encourage each contractor to apply his unique expertise and improve individual segments of the methodology. This common method of approaching the problem of engine-airframe integration should stimulate communication within the field of integration. The methodology also provides the ability to meet reasonable changes in system requirements and the problems encountered in component performance in an orderly fashion rather than in a crisis management atmosphere.

SECTION II

GENERAL DEFINITION OF TERMS

The following definitions or descriptions of many of the major terms used in this document are necessary for an understanding of the integration and cycle selection process. For convenience, the terms are grouped under several general headings to which they best apply.

2.1 TIME PHASING

- Phase - A time sequence in an aircraft development process characterized by specific types of requirements and activities.
- Conceptual Design Phase - The earliest portion of the development process, beginning with the Required Operational Capability (ROC) definition, and proceeding up to the point of selecting a general aircraft and propulsion system to satisfy the general ROC requirements.
- Preliminary Design Phase - The period where the general concepts are narrowed to a specific configuration.
- System Development Phase - The period where the design of the selected aircraft configuration is validated, the propulsion system component tests are run, and the engine testing is conducted. A system flight test program is also included in this phase.

2.2 PERFORMANCE

- Levels - The state of the technology or degree of sophistication for determining system performance at the various stages of the development process representative of data accuracy.

  Level I - Historical data and analysis; little geometric data needed. The most elemental of performance prediction techniques, used for conceptual design.

  Level II - Semiempirical and analytical predictions using a representative (though not necessarily exact) configuration of the system. Final aircraft guarantees are based on such predictions.

  Level III - Scale model or component rig data of the actual configuration being developed. This is a verification of the Level II predictions used in the aircraft guarantees.

  Level IV - Flight test and engine test data of the configuration being developed.

- Elements - Key portions of the overall system for which individual performance maps are obtained. The elements are: airframe, inlet system, exhaust system, and turbomachinery.

- Maps - Plots of the performance of the various elements over the full operating range.

  (1) Aircraft - usually in the form of drag polars (C_L versus C_D).

  (2) Inlet - examples are inlet drag versus mass flow ratio and Mach number; pressure recovery versus mass flow and Mach number.

  (3) Exhaust Nozzle - an example is aft-end drag coefficient versus aft-end area ratio and Mach number, possibly modified for plume shape effects.

  (4) Turbomachinery - examples are thrust and specific fuel consumption as a function of Mach number, altitude, and power setting.

- Target Performance - That which has not been rigorously demonstrated, but is deemed achievable at a future time.

- Demonstrated Performance - That which has been verified by actual test.

- Figures of Merit - Those parameters used to assess the performance or usefulness of one system relative to another. Examples are takeoff gross weight, range for a given payload, life cycle cost, etc.

2.3 TEST TECHNIQUES

- Aero Force and Moment Model - A wind tunnel model that defines the basic airframe aerodynamic information.

- Inlet Effects Model - The wind tunnel model used to measure inlet drags to correct the force and moment model performance to operating inlet flight conditions.

- Jet Effects Model - The wind tunnel model used to measure aft-end performance to correct the force and moment model performance to operating aft-end flight conditions.

- Metric Splitlines - Model boundaries which separate those portions of the model which have forces measured on force balance (metric) from those not measured (nonmetric).

- Aerodynamic Reference Condition - A full-scale aircraft configuration and the propulsion flow conditions to which all ΔC_D's are related

during the drag buildup. In general, this condition is chosen either for the ease with which the drag may be calculated in an analytic buildup or for the ease with which it may be measured in an experimental buildup. If an experimental buildup is used, corrections should be applied for Reynolds number effects and model mount interference.

- Operating Reference Condition - A full-scale aircraft configuration and propulsion flow conditions to which all drag increments are related when calculating aircraft performance. At this condition all drag is charged to the airframe and none to the propulsion system.

- Operating Condition - Any full-scale configuration or condition at which the aircraft may operate.

- Drag Polar - Lift coefficient versus drag coefficient for the aircraft.

- Trimmed Drag Polar - A drag polar with modifiers accounting for such effects as angle-of-attack, tail angle, surface roughness, skin friction, etc.

- Drag Buildup - The process of obtaining and adding the performance of the various elements to the basic drag polar (using the thrust/drag accounting procedure) and obtaining installed performance.

- Throttle Dependent Drags - Those drags resulting from changes in engine power lever settings which cause inlet and nozzle operating conditions to change relative to the operating reference condition.

2.4 STATION DESIGNATIONS

- A_{10} - MAXIMUM FUSELAGE CROSS-SECTIONAL AREA PER ENGINE
- A_{11} - FUSELAGE CROSS-SECTIONAL AREA AT AIRPLANE CONNECTION POINT PER ENGINE (CUSTOMER CONNECT)
- A_9 - EXHAUST NOZZLE EXIT AREA
- A_8 - EXHAUST NOZZLE THROAT AREA

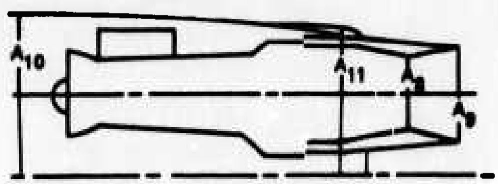


Figure 1. Engine Schematic

SECTION III

DEVELOPMENT PROGRAM EXAMPLE CASE HISTORY

Before a meaningful discussion on methods to improve future airframe/propulsion system effectiveness can be addressed, it is worthwhile to examine a historical airframe and engine integration process. The development program is divided into three phases: Phase I - Conceptual Design; Phase II - Preliminary Design; and Phase III - System Development. This example from a recent program is presented to fill in some of the details of the work involved and point out problem areas encountered developing an airframe, choosing a cycle, and matching the combination.

3.1 PHASE I - CONCEPTUAL DESIGN

3.1.1 Airframe Development - Phase I

The Conceptual Design phase began with a series of studies to define a set of system requirements which would allow the postulated threat to be met with maximum realism in technology, schedule, and cost. Toward this goal, over 60 separate air vehicle configurations were defined by one contractor alone, and weight and performance characteristics were estimated for each.

The early studies were broad in character, with a wide range of projected mission requirements in terms of payload, range, speed, and operational philosophy. These variations were considered, and trades were established to determine impact on system effectiveness, cost, schedule, and required technology.

Propulsion system integration activities during these early studies were limited primarily to engine/inlet placement to satisfy volume and balance constraints. Engine cycles consisted of spot point engine performance data; propulsion system installation losses were estimated based on historical data. Decisions resulting from these early Phase I

studies defined an airplane with the following characteristics:

a. A stability augmentation system.

b. Enhanced mission effectiveness from increased penetration speed.

c. Variable sweep wings.

As the studies continued, the effort changed from a searching process to more definitive iterations. The airframe contractors supplied the engine manufacturers with vehicle trades, mission sensitivities, and load factors as functions of engine design parameters. Engine brochures and scaling factors were provided by the engine contractors. Propulsion installation effects were investigated analytically. Base-point air vehicles were synthesized and wind tunnel models built and tested.

The program evolved into a planning stage, wherein the airframe and engine contractors were funded to prepare system specifications, engine specifications, and interface control documents. Iterations between engine and airframe became more detailed as the program progressed. Requirements such as infrared radiation suppression, radar cross section, vulnerability, and avionics became more important in the design of the engine and airframe.

3.1.2 Engine Development - Phase I

The major engine output of the Conceptual Design phase was a general propulsion system which would satisfy a set of mission requirements. Conceptual design studies of the air vehicle's defined engine size, thrust-to-weight ratio, and specific fuel consumption characteristics which led to a parametric engine cycle formulation. Parametric cycle studies defined desirable component performance characteristics. The fuel consumption and countermeasures requirements dictated the selection of a mixed flow augmented turbofan with a plug nozzle.

At this point, iterations with the airframe companies led to the definition of desirable engine technology requirements, e.g., high-stage loading compression system; air-cooled, high-temperature turbine with variable geometry. Basic technology programs were initiated to investigate the feasibility of developing these components to the desired performance levels. Light weight and durability were particularly important considerations. The results of these programs were then factored into further parametric cycle studies in terms of component performance maps.

At this point, the airframe manufacturers had completed basic airframe feasibility studies and technology requirement definitions. Engine requirements were modified based on the results of these studies and ensuing technology development. Subsequent iterations with engine cycle requirements led to the definition of an engine demonstrator configuration.

The engine demonstrator program was divided into three segments: (a) core engine program, (b) dry mixed flow turbofan, and (c) augmented mixed flow turbofan. The purpose of the engine demonstrator was to verify component performance levels and reliability and investigate component interactions.

Once the demonstrator program had been completed, engine weight and installation envelope, as well as expected life, became more realistic and more confidence could be placed in the engine performance prediction. Another series of parametric variations (small excursions in fan pressure ratio, bypass ratio, etc.) of the basic cycle were examined. Brochure information on each engine variation was transmitted to the airframe companies. It included engine performance at critical mission points, weight, installation envelope, life, and engine scaling information. Recommendations were also made to improve system practicality and cost effectiveness.

It was now possible to properly study the real integration of engine and aircraft. However, since various engine and aircraft manufacturers were in spirited competition for the ensuing system development program, complete interchange of concepts was not effected.

Phase I ended with receipt of the request for proposals by the system and engine contractors. At that point in time, sufficient information had been obtained to establish technology, schedule, and cost confidence levels to proceed with the system development.

3.2 PHASE II - PRELIMINARY DESIGN

3.2.1 Airframe Development - Phase II

The Preliminary Design phase included preparation of competitive proposals, evaluation, contract award, and an additional six months after contract go-ahead.

During the proposal activity additional configuration and performance definition studies were conducted, engine/airframe interface elements and agreements formulated, and data exchange requirements established. The two engine companies involved submitted different engine cycles. The airframe was tailored to each cycle, but time and cost constraints prevented a complete optimization of both airframe/engine cycle combinations. The performance definition was based on analytical estimates and Level II type wind tunnel test data from parametric aerodynamic force and moment models, jet effects models, and inlet models.

A finalized thrust/drag accounting system was established during the proposal activity, and a wind tunnel test program of the final configuration was planned for Phase III completion. This plan included inlet recovery and distortion/turbulence models, inlet drag models, jet effects models, aerodynamic force and moment models, and pressure loads models.

A number of trade-off studies were also conducted during Phase II. These included:

a. Configuration Optimization: optimizing for weight and cost.
b. Inlet Type: mixed versus external compression.
c. Nozzle Design: drag traded for weight and length.
d. Engine Performance Optimization: change control schedule for airflow matching and stability.

During the latter portion of Phase II, the contractors were requested to reevaluate all system requirements to arrive at the proper blend of cost versus system capabilities. Although such a study had been previously completed, the configuration definition had now reached a point that these trades could be made with a higher degree of confidence and realism. This exercise resulted in modifications to the requirements such that total system costs were reduced with minimum impact on system capability.

At the close of Phase II, the aircraft configuration and engine cycle and size were frozen. The new basepoint air vehicle included changes that were made as a result of the earlier trade studies plus the impact of further structural design definition and aerodynamic lines development. The following are examples of typical changes that were made to the configuration at this time:

a. Increase in takeoff gross weight.
b. Change in the wing size, thickness, and pivot location.
c. Change in size and location of landing gear.
d. Refairing of some fuselage lines.

Although these changes are minor (i.e., to the casual observer the configuration drawings would appear nearly identical) they did have an impact on the propulsion installation effects due to the revised flow fields in the vicinity of the inlet and nozzle. The full impact of these changes will not be known until models can be built and tested in Phase III.

3.2.2 Engine Development - Phase II

The proposal portion of Phase II of the engine development was characterized by continued cycle iterations in order to tailor the engine to the airframe. Significant modifications to the original Phase I baseline aircraft were being incorporated due to more realistic structural definition. Weight and sizing were key factors and cycle iterations were made to provide required thrust and specific fuel consumption at critical mission points while trying to minimize engine size. However,

since Phase II of the program was a highly competitive proposal period, the interchange of engine and airframe company data was reduced and integration studies thereby inhibited. The integration process, as a result, was highly iterative and time-consuming.

In some instances, the developed technology base was inadequate to meet the final set of requirements and some additional testing was required in this phase. For example, the engine manufacturer, as a result of airframe company input, decided to change from the plug nozzle to a convergent-divergent nozzle to reduce nacelle cross-section and consequently reduce both friction/interference drag (important to the subsonic mission) and wave drag (important to the supersonic mission). New mixer design studies and feasibility tests were conducted aimed at high performance and infrared radiation suppression. Static and wind tunnel tests of a scale model nozzle were conducted to obtain parametric installed nozzle performance estimates.

Following contract award, the USAF directed a six-month engine size and cycle optimization study as part of the development contract. The proposed engine had been tuned to three different proposed aircraft and not to any specific one. Hence an optimization was warranted. To accomplish the optimization effectively, a joint airframe and engine team was established. The study used the derivative approach to arrive at the final cycle selection. Small variations in the following parameters were evaluated:

- Fan pressure ratio and bypass ratio
- Compressor pressure ratio
- Fan speed at match point
- Compressor speed at match point
- Overall fuel air ratio
- Fan operating line

The installation factors used were target values and no uncertainty band was applied to the data to determine the effect on cycle selection.

The results of these perturbations along with the mission sensitivity factors were used to tune the engine to the specific airplane. The engine cycle and size were now frozen.

3.3 PHASE III - SYSTEM DEVELOPMENT

3.3.1 Airframe Development - Phase III

The System Development phase started about six months after contract award and will continue through flight test. The major activities that will occur during this time period will be:

a. Final Configuration Development -- The studies listed below will be conducted during the final configuration development activities of Phase III:

- Aircraft and mission sensitivity studies
- Airframe mold line development
- Nozzle/airframe compatibility

Aircraft and mission sensitivity studies will be conducted so that the impact of the various propulsion system performance parameters, (such as inlet recovery, drag, thrust coefficient, compressor efficiency, etc.), on aircraft/mission performance can be assessed. The results of this study will show which propulsion system factors are important and also provide data for making rapid trade-off studies. These sensitivity factors will be given to the engine manufacturer to assist his in-house "tuning" of the engine.

The airframe mold lines will be further developed. These studies will include structural design layouts and loads analysis, refined weight estimates and configuration trade-off studies. The trade-off studies will include such items as nacelle and engine tailpipe length, nozzle design/schedule, and engine envelope clearance. Performance as well as inlet/engine and nozzle/airframe compatibility considerations will be included in these studies.

Nozzle/airframe compatibility will be demonstrated by wind tunnel tests of a hot jet model. Temperature, pressure and acoustic measurements

will be used to show that the jet exhaust will not impose an unacceptable temperature or acoustic environment on aft airframe structure and surfaces. The tests will include takeoff simulation using a ground plane. The pressure measurements will be obtained with both hot and cold flow to determine whether the exhaust temperature will induce a different pressure field on the aft airframe surfaces and that drag data obtained from cold jet models will be valid.

b. Design and Fabrication -- Once the airframe mold lines are "frozen," fabrication of the airframe will begin. The structural design will be based on Level III type pressure-loads data obtained from wind tunnel tests of instrumented models. The effects of inlet flow and exhaust plume/nozzle opening will also be included. The engine company will provide data concerning nozzle area limits and anticipated pressure differentials across the nozzle. Design options such as interfairing shape, local steps, and gaps will be evaluated during this activity using empirical estimates, or where possible, "piggy back" wind tunnel testing on performance verification tests.

Inlet/nozzle schedules will be finalized during this activity. This data, along with the results from the first engine test, will be evaluated and the impact of the engine performance on mission performance will be established.

c. Performance Verification -- A preflight performance verification will be required so that any serious performance or compatibility deficiencies can be detected and corrected prior to first flight.

The inlet/airframe performance interface will be verified using data from wind tunnel tests of the aerodynamic force and moment model and the inlet drag and recovery models. These models will be updated to the final configuration. Inlet boundary layer control and bypass drags will be determined from the inlet drag model. Inlet effects on aircraft drag, lift, and moment will be accounted for as functions of power setting.

Similarly, the nozzle/airframe performance interface will be verified using the aerodynamic force and moment model and the jet effects drag models. Representative control surface deflections and wing settings will be picked for these tests. Jet effects on aircraft drag, lift, and stability/control will be determined.

Other specialized models to investigate strut/sting effects, inlet fairing effects and tunnel blockage effects will be tested to determine the impact of these factors on the accuracy of the performance data.

The inlet/engine compatibility will be demonstrated by wind tunnel tests of a full scale inlet/engine model. The tests will be conducted over a range of flight conditions and power settings. Various functional modes of the inlet and engine will be tested, including throttle chops and power bursts. The inlet control system will also be evaluated during these tests. These tests will require especially close coordination and participation of the airframe and engine companies.

d. Flight Evaluation -- The flight evaluation activity will provide the final performance/compatibility verification. During these tests instrumented and calibrated engines will be used in conjunction with instrumented airframes. The flight test data will be acquired over a range of power settings at various altitudes and Mach numbers. After the flight evaluation phase is concluded a determination will then be made regarding the system suitability for operational use. If so, the production phase will be initiated.

3.3.2 Engine Development - Phase III

During the System Development phase, a series of Audit Gates will be conducted in which both the airframe and engine companies will present the propulsion system development status and critique the other's program. A summary of the review will then be presented to the USAF.

The System Development phase for the engine can be broken down into the following stages:

a. Design -- During the design stage detailed performance and control schedules will be defined for the final engine cycle. Mechanical design of the engine, components, and component test vehicles will be conducted. The primary tasks of aircraft/engine integration during this stage will be:

- Free exchange of design data reports addressing the installed propulsion system
- Agreement on engine/inlet interface plane for distortion/recovery definition
- Transmittal of engine steady-state and dynamic decks to the airframe company
- Mission sensitivity factors transmitted to the engine company

b. Component Test -- The component test stage will include scale model and full scale component performance and mechanical integrity evaluation. Integration related testing will include:

- Joint nozzle/afterbody wind tunnel testing
- Scale model inlet testing and subsequent airframe/engine company agreement on design distortion limits.

An installed engine status deck will be initiated which will include component test maps, and inlet and afterbody drag test results. Status inlet distortion screening curves will be developed based on the design requirements in the Interface Control Document coupled with distortion sensitivity results from fan and compressor component tests.

c. Core Engine Development -- The core engine will be used for continued compressor and high pressure turbine development, as well as basic engine mechanical system development. Steady-state temperature and pressure distortion testing will also be conducted on the core using maximum anticipated distortion levels. Distortion stall margin will be determined and stability stack-ups will be updated and transmitted to the airframe company. Transient operation with both uniform and distorted inlet conditions will be investigated.

d. Turbofan Development Testing and PFRT -- Turbofan development testing will culminate in performance, stability, and endurance testing at simulated flight conditions. This will lead to the engine pre-flight rating test (PFRT). During these stages, the estimated PFRT status steady-state performance deck will be transmitted to the airframe company.

e. Flight Evaluation -- Engine operational capability, performance, and stability characteristics will be evaluated over the entire air vehicle flight envelope.

At this point the engine and airframe contractors will know whether the foregoing program was conducted properly.

SECTION IV

THRUST/DRAG ACCOUNTING

If a decision on cycle selection is to be made with a reasonable degree of confidence, a complete, accurate, and logical system for accounting for all forces acting on the vehicle must be implemented by both the engine and airframe contractor from the very start of the development program.

The need for a thrust/drag accounting system arises largely from the inability to determine, in one calculation or one test, the total force on the complete airplane system, with simultaneous real inlet and exhaust system operation. The total force build-up brings together many pieces involving separate disciplines (i.e., propulsion and aerodynamics) and even separate companies (i.e., engine and airframe companies). The accounting procedures must, therefore, insure that the appropriate information can be communicated between disciplines and between companies, as well as to the government, in a way that permits an accurate system performance evaluation and thus the evolution of a near optimum system.

At the heart of any thrust/drag accounting system is the definition of three major items: the split between internal and external forces; the split in the external force between propulsion system drag (installation loss drags) and the airframe system drag (reflected in the drag polar); and the element performance map formats required to build up thrust and drag consistent with these definitions.

The selection of the system described below is based on three criteria. First, and most important, is the requirement for accuracy in predicting the overall thrust-minus-drag performance. Secondly, the performance integration procedures should provide meaningful performance visibility for the airplane system elements and subsystems. Finally, the system should be applicable with consistent definitions throughout an entire airplane development program.

4.1 INTERNAL/EXTERNAL FORCE DEFINITIONS

The internal force is defined as the difference between nozzle static gross thrust and engine-streamtube ram drag. In the case of an analytical performance build up, as well as the case of the jet-effect is model simulation of real exhaust system operation, the "static gross thrust" is the gross thrust corresponding to the static nozzle thrust coefficient at the operating total pressure ratio and the actual nozzle mass flow rate. In calculating the internal force of the aerodynamic force and moment model the nozzle gross thrust can correspond to either static or wind-on conditions, and the same definition must be used when these flow-through nacelle conditions are simulated with the jet-effects model as the reference point for external force increments. The "engine streamtube" includes all of the airflow demand at the engine face as well as any secondary airflow captured by the inlet and ducted around the engine to the exhaust system. Any additional airflow captured by the inlet and ducted overboard through bleed or bypass systems is not part of the "engine" streamtube.

The external force is then, by definition, the difference between the total force on the airplane and the internal force defined above. As a consequence of these definitions, the external force includes: the additive drag on engine streamtubes; drag of all inlet surfaces (e.g.; a bleed system) wetted by streamtubes other than engine streamtubes; and the change in nozzle thrust forces between static and wind-on conditions.

4.2 THRUST/DRAG DEFINITIONS

The total force F_{TOTAL} in the flight direction on an aircraft in level flight at a given attitude, Mach number, and altitude, is described by the following equation:

$$F_{TOTAL} = \underbrace{\underbrace{F_{N_{ENG}}}_{\text{engine system}} + \Delta F_{N_{INL}} + \Delta F_{N_{\substack{EXH\\SYS}}} + \Delta F_{N_{TRIM}}}_{\text{propulsion system net}} \underbrace{- D_{REF} - \Delta D_{INL} - \Delta D_{\substack{EXH\\SYS}} - \Delta D_{TRIM}}_{\text{airframe system}} \tag{1}$$

F_{TOTAL} is a summation of all the forces on the vehicle resulting from all engines, inlets, and exhaust systems. The first four terms on the right side of the equation combine to form, by definition, the propulsion system installed net thrust, and the last four terms, the airframe system drag reflected in the drag polar.

The engine net thrust, $F_{N_{ENG}}$, is defined according to the internal force definitions of the Internal/External Force Definitions section. It accounts for the effects of inlet internal performance, nozzle internal (static) performance, engine bleed, and power extraction.

The remaining terms in Equation 1 are keyed to the concepts of drag polar operating reference conditions and wind tunnel aerodynamic reference conditions. The expression "operating reference conditions" is used here specifically to distinguish these conditions from the wind tunnel "aerodynamic reference conditions" which are: (a) used on the aerodynamic force and moment model; and (b) reproduced on the propulsion models to obtain datums for propulsion drag increments. The operating reference conditions are those conditions, representative of realistic flight conditions, to which, by definition, the drag polar corresponds. The definitions apply whether the drag polar results from analytical buildup procedures, wind tunnel tests, or flight test. A description of both "aerodynamic reference conditions" and "operating reference conditions" for both the inlet and exhaust system is given in Table I.

The term D_{REF} in Equation 1 is then the external force associated with the aerodynamic force and moment model at the aerodynamic reference conditions. The term ΔD_{INL} is the non-throttle dependent external force increment between the aerodynamic reference and the operating reference inlet conditions, and $\Delta F_{N_{INL}}$ is the increment between operating reference conditions and any given inlet throttle-dependent condition.

Similarly $\Delta D_{EXH\ SYS}$ and $\Delta F_{N_{EXH\ SYS}}$ represent the drag and thrust parts of the total exhaust system increment which would be measured with a jet-effects model in an experimental performance buildup. The use of

TABLE I

SUMMARY OF AERODYNAMIC REFERENCE CONDITIONS AND OPERATING REFERENCE CONDITIONS

	AIRFRAME	INLET	EXHAUST SYSTEM
AERODYNAMIC REFERENCE CONDITIONS	AERO MODEL TESTED AT THESE CONDITIONS. CRITERIA FOR SELECTION INCLUDE: 1. CAN BE RELIABLY REPRODUCED IN THE SEPARATE INLET AND NOZZLE TESTS. 2. FACILITATES ACCURATE MEASUREMENT OF BOTH AERO MODEL DRAG AND ASSOCIATED PROPULSION INCREMENTS FROM THE SEPARATE TESTS. 3. REPRESENTS REALISTIC CONDITIONS MODIFIED AS NECESSARY TO SATISFY ABOVE CRITERIA. AIRPLANE SYSTEM DRAG POLAR NEED NOT CORRESPOND TO THESE AERODYNAMIC REFERENCE CONDITIONS.	GENERALLY REALISTIC GEOMETRY, NO BLEED OR BYPASS FLOW (WHICH ARE DIFFICULT TO REPRODUCE AT DIFFERENT SCALES). MASS FLOW RATIO SELECTED TO MINIMIZE AERO MODEL LIP SEPARATION, WHICH IS MORE ACCURATELY SIMULATED ON THE LARGER SCALE INLET SPILLAGE DRAG MODEL. THUS THERE WILL BE MINIMAL SPILLAGE DRAG AT THIS MASS FLOW RATIO.	REALISTIC GEOMETRY, IF FEASIBLE, BUT MODIFIED WHERE NECESSARY TO SATISFY AERO MODEL REQUIREMENTS. RAM PRESSURE RATIO (SINCE AERO MODEL USES FLOW-THROUGH PROPULSION SIMULATION).
OPERATING REF CONDITIONS	THE CONDITIONS TO WHICH THE AIRPLANE SYSTEM DRAG POLAR CORRESPONDS, BY DEFINITION. THESE CONDITIONS CORRESPOND APPROXIMATELY TO A SPECIFIED ENGINE POWER SETTING, USUALLY MAXIMUM POWER, BUT WOULD NOT BE CHANGED FOR MINOR ENGINE VARIATIONS.	REALISTIC GEOMETRY, BLEED FLOW, BYPASS FLOW AND INLET MASS FLOW RATIO, CORRESPONDING TO SPECIFIED ENGINE POWER SETTING AND ACTUAL INLET OPERATING CHARACTERISTIC.	REALISTIC AFT-END GEOMETRY AND PRESSURE RATIO (BOTH P_{T8}/P_{∞} AND P_e/P_{∞}) CORRESPONDING TO SPECIFIED POWER SETTING.

the aerodynamic force and moment model and the jet-effects model (with faired-over inlets) in establishing the thrust-drag split is illustrated schematically in Figure 2. An example of the handling of jet-effects model data is given in Figure 3. The total increment from aerodynamic reference to operating conditions has been divided into the two terms, $\Delta D_{EXH\ SYS}$ and $\Delta F_{N_{EXH\ SYS}}$ with the definition of the operating reference conditions which correspond closely to one of the potential real operating points.

The terms on the right side of Equation 1, other than the trim terms, represent the thrust/drag buildup at a reference control surface angle. The procedures outlined here are also directly applicable to lift buildups and, with some modification, to pitching moment buildups. The determination of lift, drag, and pitching moment in this way as a function of control surface angle and angle-of-attack permits the construction of a trimmed drag polar at operating reference conditions. Thus, the term ΔD_{TRIM} in Equation 1 is the external force difference associated with changing from the reference control surface angle to the control surface angle required for trim.

Changes in trim drag increments associated with operation at propulsion system conditions other than operating reference conditions are likely to be very small in most cases. If not, however, they should be included in $\Delta F_{N_{TRIM}}$, which becomes one of the throttle-dependent force increments accounted for in the installed propulsion system performance.

An analytical performance buildup would be handled in a manner completely analogous to the experimental buildup, except that wind tunnel aerodynamic operating conditions would not be treated. For example, the aft-end drag already accounted for in a wing-body drag calculation, which is, analogous to the reference drag level shown in Figure 3, could become the zero point for aft-end exhaust system drag increments. The drag polar is still corrected to operating reference conditions, and $\Delta F_{N_{EXH\ SYS}}$ still accounts for the effect of operating at real aft-end conditions different from the operating reference conditions.

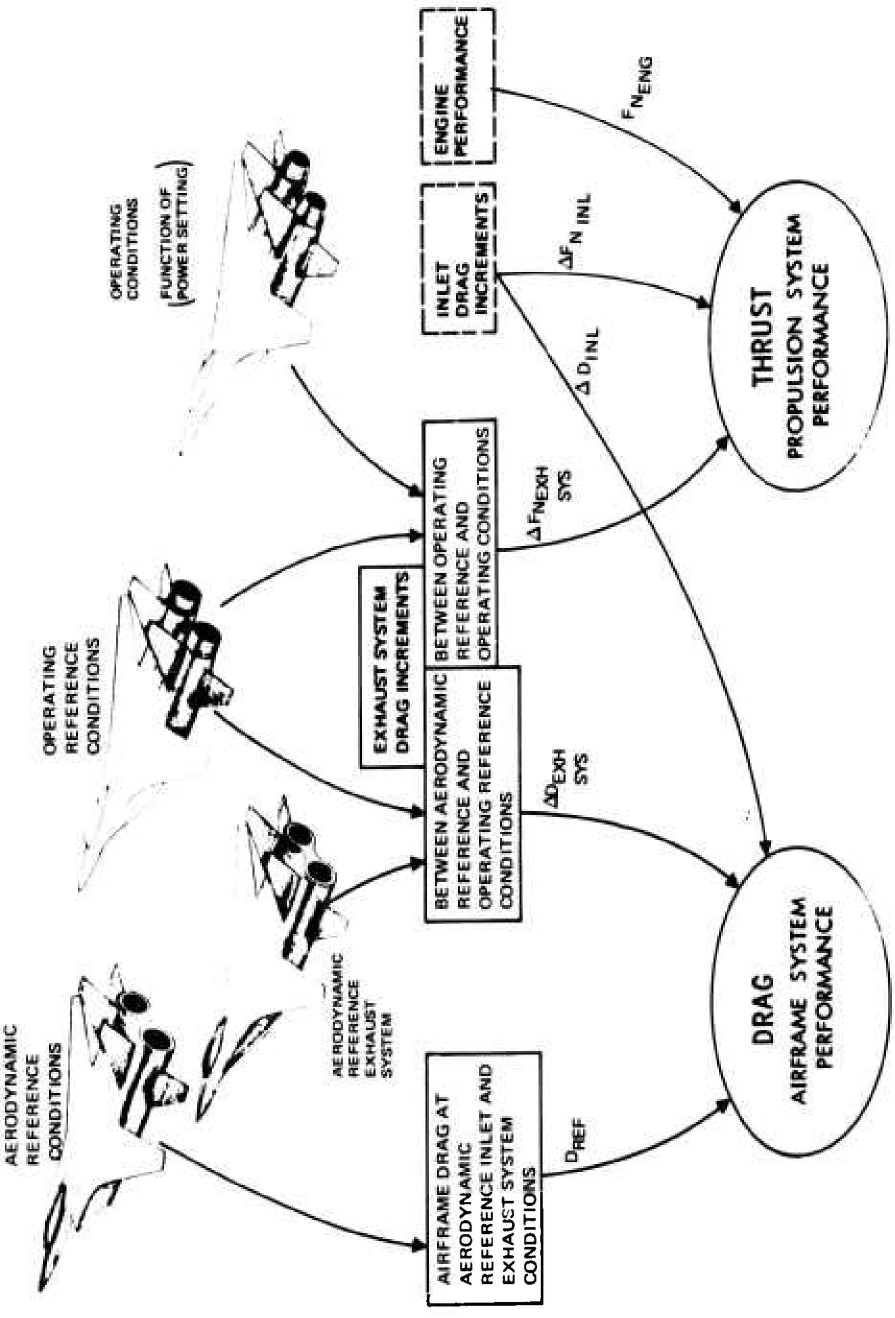


Figure 2. Definition of Thrust and Drag

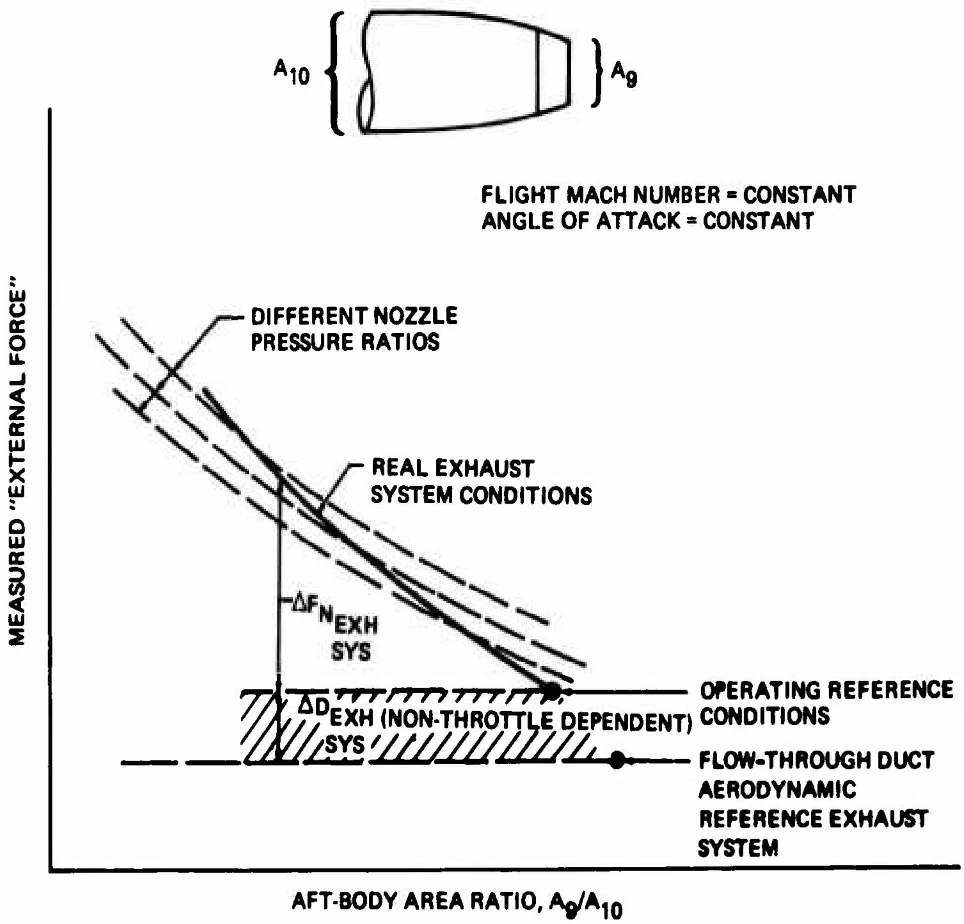


Figure 3. Example of Exhaust System Performance Data

Since the drag polar is not constrained to correspond exactly to aerodynamic force and moment model reference conditions, there is considerable freedom in an experimental buildup to tailor the aerodynamic reference conditions to ensure that they can be precisely reproduced on the inlet-drag and jet-effects models, thereby minimizing errors in the overall thrust-minus-drag buildup.

The use of realistic operating reference conditions corresponding to a specified power setting and the use of a static thrust coefficient in defining nozzle gross thrust offer major benefits in terms of two of the criteria identified in the Introduction for selecting the accounting system. First, performance visibility for airframe system and propulsion system performance is achieved. Thus, the drag polars of competing configurations using the same engines can be meaningfully compared. (The installation loss drag penalties associated with reduced power settings can similarly be directly compared.) Secondly, the thrust/drag definitions can be maintained in a consistent manner throughout an entire airplane development program. The evolution of drag polars and installation losses can be tracked from the early mission definition studies, through wind tunnel programs, and into the flight test programs. The reduction in the uncertainty bands associated with improved geometric definition of the configuration and the use of higher level performance evaluation methods can be traced with a common set of thrust/drag accounting definitions.

4.3 AERODYNAMIC FORCE AND MOMENT MODEL

The aerodynamic force and moment model, of the type shown in Table II, Model A, has been used to generate the basic aerodynamic data for most past aircraft development programs. These data include both drag polars and longitudinal stability characteristics.

The model is sting supported and operates at flow-through conditions, consequently, the aft-end flow field and aircraft propulsion system airflows are not simulated. The nozzle pressure ratio on the aerodynamic force and moment model is always less than the engine operating conditions.

The inlet mass flow ratio can be either greater or less than the actual flight condition being simulated. Only limited evaluations of engine/ airframe integration can be accomplished with this basic data. Consequently, corrections must be made to these data to properly predict aircraft performance. The corrections for proper inlet airflow and nozzle pressure ratio are established by using inlet drag and jet-effects models (Table II, Models B and C, respectively). The inlet drag and jet-effects models have splitlines, as shown, which separate the metric and non-metric parts of the model. The forces on the metric portion are measured using a drag balance. The effect of the support sting on the aft-end flow field can be obtained by testing on a jet-effects model.

The inlet and nozzle/aft-end data needed for corrections are generated over a range of airflow and nozzle pressure ratios, covering actual flight conditions as well as the aerodynamic model flow-through conditions. The data at flow through conditions are required in order to correlate the inlet drag, jet effects and aerodynamic model data. Properly combined, these data permit accurate determination of total aircraft drag. The separate values of inlet and nozzle/aft-end drag may also be readily defined over a wide range of typical operating conditions.

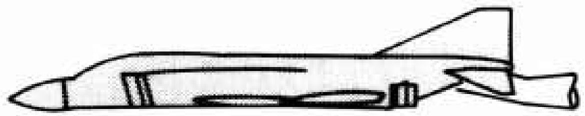
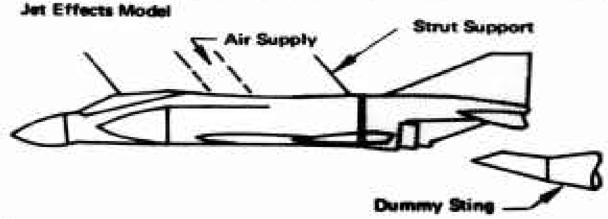
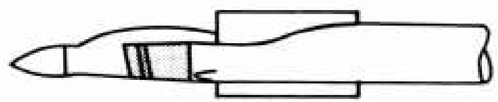
4.4 PROPULSION INSTALLATION PERFORMANCE DATA

A continuous flow of information exchange between the airframe company and the engine manufacturer is required throughout the entire airplane development process. Definition of a thrust/drag accounting system is necessary to facilitate communication between the engine and airframe interfaces and minimize error through proper accounting of the system forces. Installation requirements and formats can then be defined to enable comparison and selection of the inlet and nozzle system.

Standardized formats for these performance maps greatly simplify data interchange between engine and airframe manufacturers and the government. The formats also aid in comparing element performance

TABLE II

MODEL DESCRIPTION

Aerodynamic Force and Moment Model  A	**Model Characteristics:** All forces on the model are measured and a flow through inlet and exit are regulated by an orifice internal to the model	**Test Variables:** Mach numbers, angles of attack, and mass flow ratios and inlet ramp positions should encompass actual flight values
Jet Effects Model  B	The afterbody (shaded) drag force is measured while the jet flow from the nozzle exit is controlled remotely. A model of the sting may be placed adjacent to the model to determine its effect.	Mach numbers, angles of attack, jet total pressure ratios and nozzle geometries should encompass actual flight values. Nozzle geometries and pressure ratio conditions duplicating the force and moment model should be tested. Support system interference effects may be tested on this model or the aerodynamic force and moment model.
Inlet Model  See Fig. 5 C	The force on the inlet (shaded) is measured and the flow is controlled by a variable orifice.	Mach numbers, angles of attack, mass flow ratios and inlet geometry should encompass actual flight values

characteristics and in tracking the element performance predictions versus time. The most significant propulsion installation element performance maps are:

a. Inlet maximum flow capacity

$$\frac{W_a\sqrt{\theta_2}}{\delta_2} = f(M_\infty)$$

b. Inlet recovery

$$\eta_R = f\left(\frac{W_a\sqrt{\theta_2}}{\delta_2 A_c}, M_\infty\right)$$

c. Inlet drag (throttle-dependent)

$$\Delta C_{D_{INL}} = f\left(\frac{W_a\sqrt{\theta_2}}{\delta_2 A_c}, M_\infty\right)$$

d. Afterbody drag (throttle-dependent)

$$\Delta C_{D_{AFT}} = f\left(\frac{A_9}{A_{10}}, M_\infty, \frac{P_{S9}}{P_\infty}\right)$$

e. Nozzle internal performance

$$C_V = f\left(\frac{P_{T8}}{P_\infty}, \frac{A_9}{A_8}, \gamma\right)$$

<u>Nomenclature</u>

A_c	Inlet Capture Area
A_8	Nozzle Throat Area
A_9	Nozzle Exit Area
A_{10}	Maximum Fuselage or Nacelle Cross-Sectional Area (Per Engine)
$\Delta C_{D_{AFT}}$	Throttle Dependent Aft Body Drag
$\Delta C_{D_{INL}}$	Throttle Dependent Inlet Drag
C_V	Nozzle Velocity Coefficient

M_∞	Freestream Mach Number
P_{S9}	Nozzle Exit Static Pressure
P_{T8}	Nozzle Total Pressure
P_∞	Freestream Ambient Pressure
W_a	Total Airflow
γ	Ratio of Specific Heats
δ_2	Corrected Inlet Total Pressure $(P_{T2})/14.696$
η_R	Ram Recovery
θ_2	Corrected Inlet Total Temperature $(T_{T2})/519$

4.5 MAP FORMATS

The map formats are shown in Figure 4. These map formats allow development and evaluation of engine and element designs and control schedules on an installed (thrust-minus-drag) basis, taking into consideration the compressor/inlet flow conditions and the power sensitive portions of inlet and afterbody drag.

The format for inlet maximum mass flow capacity presents corrected airflow per unit inlet capture area as a function of flight Mach number. This format allows the inlet size to be determined given the engine demand corrected flow. Both inlet recovery and the throttle dependent increment of inlet drag are represented as functions of engine corrected airflow per unit capture area for lines of constant flight Mach number. Inlet performance presented in these map formats allows sizing of the inlet for any change in inlet airflow schedule or engine size and determination of recovery and drag for all engine power settings and flight conditions. The throttle dependent increment of total inlet drag includes the sum of bleed drag, bypass and spillage drag. This increment is relative to the "operating reference" condition consistent with the drag polar definition as defined by the thrust/drag accounting system.

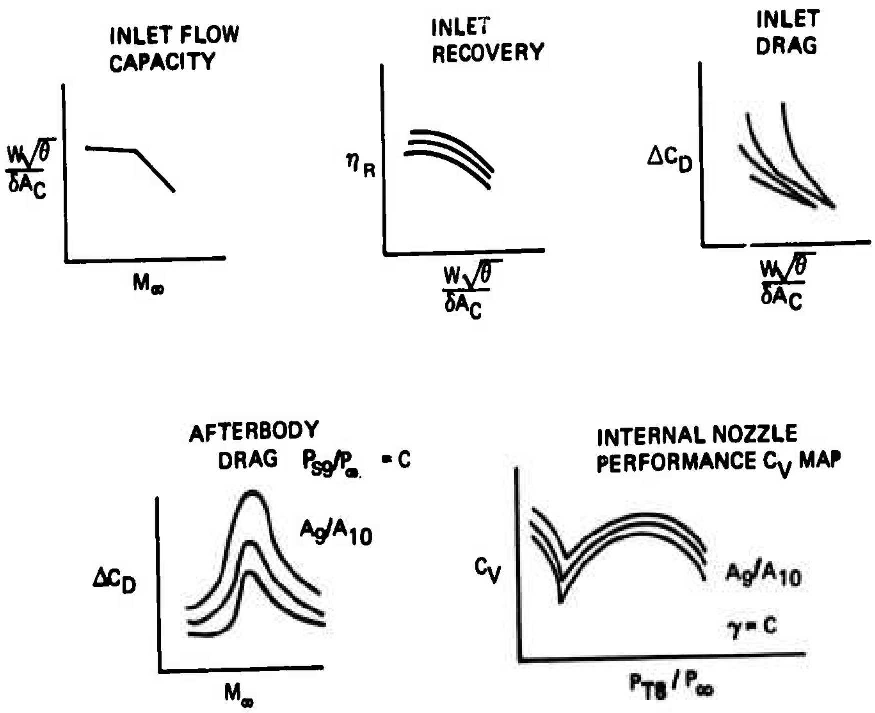


Figure 4. Inlet and Exhaust System Element Performance Map Formats

The afterbody drag map format presents the throttle dependent afterbody drag as a function of total afterbody closure area ratio (A_9/A_{10}) and flight Mach number. The afterbody closure area ratio is the ratio of nozzle exit area to the maximum fuselage cross-sectional area. The drag coefficient is referenced to A_{10}. Plume effects may be represented by nozzle static pressure ratio variations holding A_9/A_{10} and Mach number constant. The throttle sensitive increment is defined relative to the "operating reference" value of A_9/A_{10} consistent with the drag polar as defined by the thrust/drag accounting system.

The internal nozzle performance map format presents the nozzle velocity coefficient (C_V) as function of nozzle total pressure ratio (P_{T8}/P_∞) and nozzle exit to throat area ratio (A_8/A_9). Maps may be presented for different nozzle temperatures or specific heat ratios (γ).

SECTION V

WIND TUNNEL TEST TECHNIQUES

The selection of the correct engine cycle depends upon (1) proper accounting of all thrust, drag, and lift effects, and (2) the accuracy of the basic data. Currently, the most widely accepted approach to obtaining the required engine/airframe integration data involves the use of the three wind tunnel models shown in Figure 5. The aerodynamic force and moment model, jet effects model, and inlet drag model are tested over a range of conditions which simulate those of the vehicle under consideration by allowing the various forces to be combined as described in Chapter IV. There are, however, certain problems associated with this approach to aircraft performance prediction. Specifically, there are five causes of data uncertainties:

a. Model support systems
b. Metric splitline locations
c. Model mass flow
d. Model scale
    - Reynolds Number
    - Roughness Correction
    - Protuberance Correction
e. Wind tunnel limitations
    - Blockage
    - Shock Reflections

The uncertainty introduced by each of these elements can be minimized by utilizing appropriate correction procedures. However, the absolute level of this uncertainty has not been established in most cases. Considerable research and development work is required to attain more accurate test techniques. In this section, a discussion of pre-test preparation is provided, recent advances in test techniques are described, and estimates of data uncertainties are presented.

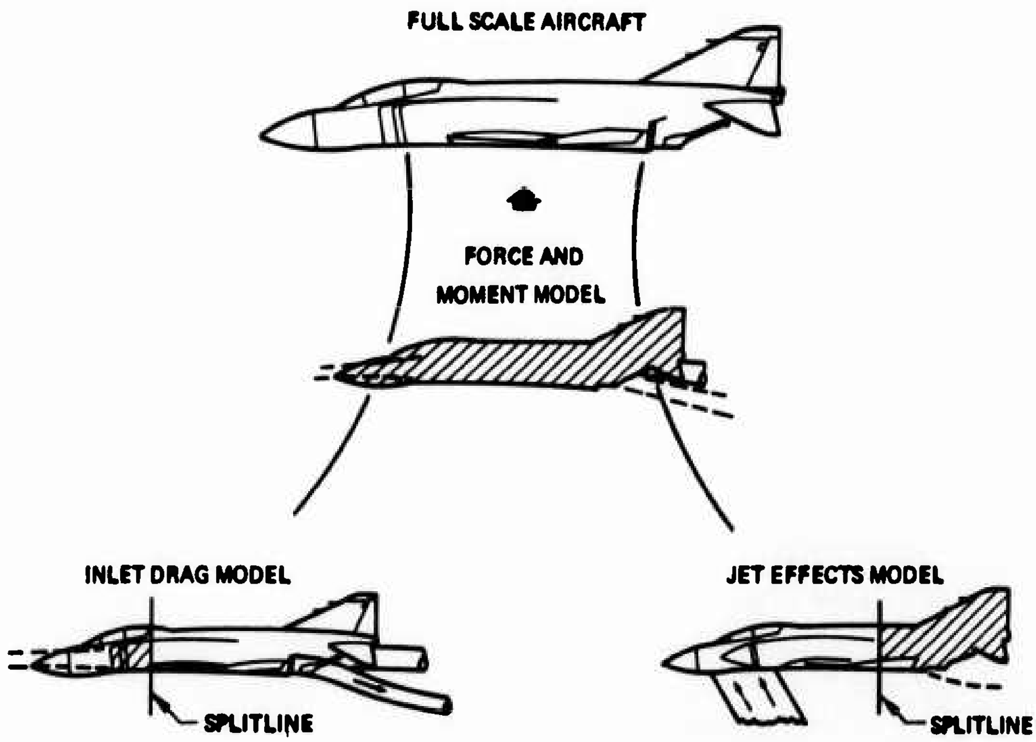


Figure 5. Projection of Full Scale Aircraft Performance

5.1 PRE-TEST PREPARATIONS

The success of a wind tunnel test program depends strongly upon the thoroughness of the pre-test preparations. These activities should include (a) detailed contractor coordination meetings with USAF and test facility personnel, (b) selection of instrumentation, model type, and test procedures, (c) prediction of accuracy, and (d) prediction of test results.

The coordination meetings serve primarily as a technical information and methodology transfer mechanism. Here, previous experience of all participants is used to solve potential problems. Further, the methodology base is broadened for future programs.

Experience has shown that a detailed prediction of data repeatability at this time will permit identification of the major error sources. Then, steps can be taken to eliminate or minimize them by changes in instrumentation, hardware, or test procedures.

Pre-test prediction of test results is necessary to establish bounds upon the instrumentation and hardware requirements. During the test program, comparison of data and prediction will often provide first indication of errors in instrumentation or procedures; alternately, it can provide guidance when diagnosing errors or examining peculiar test results. Pre-test prediction also exercises the procedures without benefit of hindsight; any estimations necessary in the procedures will be true estimates and not guesses educated by the test results. Comparison of pre- and post-test analyses can lead to improvements in prediction techniques.

5.2 MODEL SUPPORT SYSTEMS

Most model support systems inherently introduce data uncertainties because of flow field interference effects. This problem is most significant for jet effects models because the support size must be increased to route the air supply required for jet simulation. In most

thrust/drag accounting systems it is assumed that the interference due to the jet effects model support does not change with aft-end geometry or jet pressure ratio. Consequently, the required correction increments from the aerodynamic force and moment model can be obtained without determining this interference. Depending upon the support system configuration, this assumption can lead to extremely large data uncertainties. Thus, it is mandatory that the interference characteristics be determined for candidate jet effects model support systems. Currently, four different approaches are under consideration for jet effects model testing:

a. One technique employed in the past to eliminate the strut effect on jet effects models has been to use a nose mounting system where the nose reached far upstream, sometimes to the wind tunnel plenum. A variation of this technique would extend the nose of the model and mount this extension on a strut far enough upstream to avoid creating major cross section area variations in the region of the maximum model cross-section area, Figure 6A. This type of mount affects fuselage flow fields and boundary layer development.

b. Another test option for the jet effects model is the wing tip mount, Figure 6B. While a system of this type does eliminate the strut mount, the effect of wing distortion (required for passage of nozzle high-pressure air) and mounting pylons has not yet been determined. Also, significant flow field distortion is anticipated at angle-of-attack.

c. Another possible model mounting system makes use of dual sting mounts entering the exhaust nozzles, Figure 6C. These probably require no model aft-end geometrical distortion and can be used to route the air supply lines. Jet exhaust simulation is provided by annular jets issuing over the stings. Of course, this support approach could not be used for testing plug nozzle configurations, but it could be used on the aerodynamic force and moment model (Figure 6C).

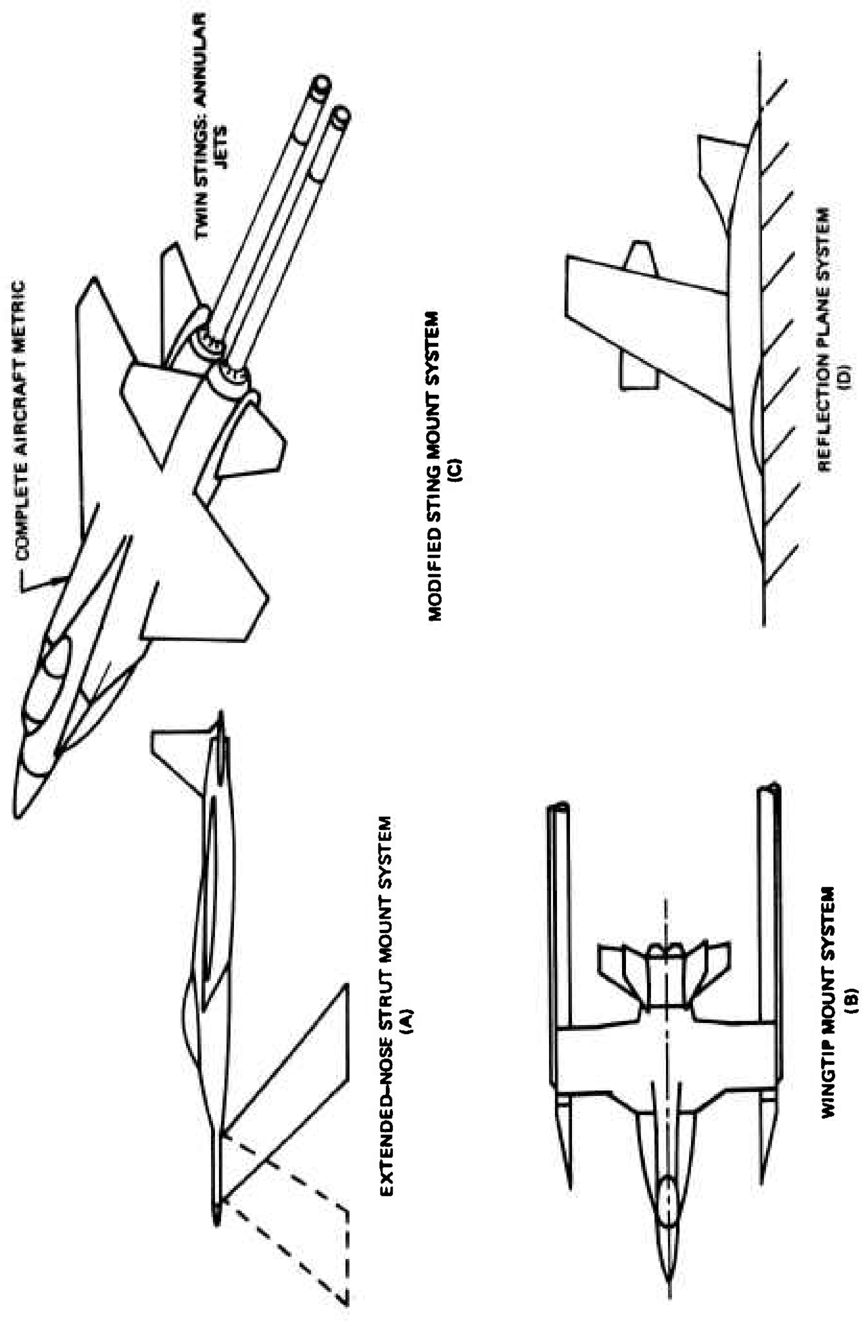


Figure 6. Jet Effects Model Support Systems

d. The fourth mounting system is a half-model mounted against a reflection plane, Figure 6D. This system removes all support strut affects and allows the model blockage in the tunnel to be reduced considerably. It is unsuitable, however, for configurations with close-coupled fuselage-mounted engines; there may also be some problems associated with tunnel wall boundary layer.

5.3 METRIC SPLITLINE LOCATIONS

The inlet drag and jet effects models are divided by splitlines (Figure 5), which separate the metric and nonmetric sections of the model. The location of the splitline may cause some data uncertainty. The forces on the metric portion are measured with a drag balance. The metric splitlines must be properly located to accurately measure the entire effects. In jet effects tests, pressure disturbances due to aft-end changes may propagate forward of the splitline and not be measured. Similarly on inlet drag models, mass-flow-induced disturbances may propagate aft of the splitline and therefore not be accounted for.

The interaction of forebody with afterbody and vice versa can be attacked by utilizing models which have separate balances for the different elements. Some attempts have been made to do this including a metric model with a separately metric inlet and a model with the fuselage, afterbody, and nozzle all separately metric.

5.4 MODEL MASS FLOW

Jet effects models are commonly used to attain nozzle/aft-end flow field simulation. Typically, this approach has two shortcomings. First, the hot exhaust plume of the aircraft is simulated with cold air. Secondly, the inlets of the model are faired over to provide room to route the air supply. The effect of not fully simulating the exhaust characteristics is being investigated, but no results are currently available. The effects of the inlet fairing are relatively small subsonically. However, supersonically, the flow field disturbance caused by the inlet fairing can significantly change aircraft trim drag characteristics.

A number of corrections to aerodynamic force and moment model test data are required because of improper mass flow through the model. In fact, the primary purpose of the inlet drag and jet effects models is to correct the aerodynamic force and moment model data to the proper airflow conditions. Thus, three models are required. The propulsion simulator, being evaluated under another Air Force program, offers a potential solution to this problem by providing simulation of both inlet and nozzle flow conditions simultaneously. Further, the fairing induced uncertainty would be eliminated by using the simulator.

5.5 MODEL SCALE

Currently, in aircraft performance projections, scaling considerations are limited to friction corrections based on Reynolds number. These can be relatively large corrections. However, sources have indicated that other drag forces may be affected by Reynolds number. The results appear to be in conflict. Flight and model tests conducted by NASA-Lewis with podded J-85 engines installed under an F-106 aircraft showed contradictory trends with Reynolds number. The investigators presented a plausible explanation for this discrepancy. However, other factors such as changes in scale, nonsymmetrical flow separation, and tunnel effects may have had a significant influence on the results.

Corrections for protuberances and surface roughness are not adequately developed and are currently based on analytical and limited empirical data. Such corrections can be large.

5.6 WIND TUNNEL LIMITATIONS

Wind tunnel blockage and shock reflections present major sources of testing uncertainties at transonic speeds. Most wind tunnel facilities have specified blockage limitations; however, associated testing uncertainties are not generally known. When limits are defined, they are usually not adequate to accommodate the wide variety of model shapes, length, frontal areas and support systems.

The results of many previous tests serve to emphasize the critical nature of transonic testing and indicate the care required to obtain good results. An apparent solution is to employ small models in large tunnels and this approach should be actively pursued. However, because of practical limitations in tunnel and model sizes, this approach cannot be completely implemented.

5.7 DATA UNCERTAINTIES

The uncertainty in predicted aircraft performance is dependent, of course, upon the time placement in the development cycle. In the conceptual design phase, Level I data is used to evaluate candidate aircraft concepts. The level of uncertainty here may be large because the available data is not adequate, and the configurations are not completely defined. Therefore, a major objective should be to develop an empirical data base of sufficient accuracy to permit confident preliminary design engine/airframe integration studies. The accuracy of this data base is wholly dependent upon the test techniques used. The techniques used to generate Level II and III data, in the preliminary design and system development phases, respectively, also contribute significantly to the uncertainties in predicted performance. Consequently, it is important that the potential levels of data uncertainty be identified, and action taken to minimize them.

In the previous subsections, recent advances in test techniques have been described. The potential (estimated) range of data uncertainty associated with these test techniques is summarized in Table III. It should be pointed out that these values are estimates and may actually be significantly different. Further, these increments are not necessarily additive, nor would they all occur in one system. The uncertainty increments are presented in terms of delta drag coefficients based on aircraft wing area. As a point of reference, a typical value of aircraft subsonic cruise drag is 0.0350.

TABLE III

POTENTIAL DRAG DATA UNCERTAINTY RANGE

SPEED REGIME / SOURCE	SUBSONIC		TRANSONIC ($0.9\ M_o - 1.5\ M_o$)		SUPERSONIC	
	INLET	AFT END	INLET	AFT-END	INLET	AFT-END
MODEL SUPPORT SYSTEMS	N/A	.0020	N/A	.0050	N/A	.0030
METRIC SPLITLINE LOCATIONS	.0010	.0010	.0010	.0005	.0010	0
MODEL MASS FLOW						
HOT GAS	N/A	.0020	N/A	.0020	N/A	.0020
INLET FAIRING	N/A	.0010	N/A	.0010	N/A	.0010
	SYSTEM*		SYSTEM*		SYSTEM*	
MODEL SCALE	.0020		.0050		.0010	
WIND TUNNEL LIMITATIONS	.0020		.0050		.0005	

* SYSTEM MEANS COMBINED UNCERTAINTY RESULTING FROM INLET DRAG, JET EFFECTS AND AERODYNAMIC FORCE AND MOMENT MODELS

SECTION VI

LESSENING THE RISK OF INCORRECT CYCLE SELECTION

At the time the engine and aircraft designs are frozen, an area of uncertainty exists as to the actual performance capability of the proposed system. At this time, much of the wind tunnel and structural design work remains to be done. Elemental test data and performance predictions that do exist are not absolute, as previously discussed. As the structural design becomes more realistic, changes are forced in the airframe geometric lines altering the predicted aerodynamics. Furthermore, the possibility always exists that mission requirements will change.

The extent of the total possible mismatch resulting from the uncertainty bands will not be known until flight test. In addition to the direct effects on aircraft performance, these uncertainties may also mean that the engine cycle is no longer the best for the mission.

There is a need, therefore, to consider not only the data requirements and timing for successful cycle selection but also the sensitivity of the selected cycle to changes in inputs. It is the purpose of this section to discuss the extent of this sensitivity and to consider how to minimize the risk of failing to achieve the desired development goals.

6.1 SENSITIVITY ANALYSIS

The sensitivity of engine cycle and size selection to the uncertainty in the propulsion system installation losses is considered to illustrate the need for a sensitivity analysis during the early stages of the development of a new airplane. The example considered in this section shows that when large installation losses are considered, the optimum cycle is significantly different from that which would be optimum at a lower level. If the development of a new engine is to proceed with confidence, uncertainty bands must be established for all major elements in the airplane system, including the inlet, engine, exhaust system, and

airframe. The upper and lower levels of these uncertainty bands would then be used in sensitivity analyses to evaluate the impact of these uncertainties on critical decisions regarding the engine cycle development.

Let us assume a sensitivity study for the early development phase of a bomber has been completed. For illustrative purposes, the philosophy of this study together with comments on the main lesson learned are explained below:

a. The airplane configuration selected for use in this sensitivity study was a Mach 2.2 bomber with both supersonic and subsonic mission requirements.

b. Three engines with sea level static bypass ratios of 1.0, 2.0 and 3.0 were picked to show the influence of afterbody drag uncertainty on cycle selection. Bypass ratio was selected as a parameter only because of its relatively large impact on net thrust lapse rate (change in net thrust with altitude and Mach number), fuel flow, and airflow schedules.

The engine thrust lapse characteristics are particularly important since engine sizing points may be affected. Changes in size have a large effect on airplane performance in both subsonic and supersonic missions. Any increase in engine size and weight is reflected as decreased available volume and weight for fuel when mission total weight is held fixed.

c. The engine which is selected as "optimum" for a multimission airplane is dependent on the emphasis placed on the performance required for one mission relative to the other. Obviously, unless both the subsonic and supersonic mission range requirements were met exactly, subsonic range may be traded for supersonic range by varying engine size, wing loading, etc. The following ground rule is used in this study in selecting an engine: If both mission ranges are below the design requirements, the engine size and wing loading are selected such that both mission ranges are a maximum or have equal decrements from the design range requirement.

d. A significant aspect of most sensitivity studies is that perturbations in the independent variables are constant throughout the flight envelope. In this sensitivity study, however, the uncertainties in afterbody drag were estimated for each critical flight operating condition. The magnitude of the perturbation was a function of not only altitude and Mach number, but power setting as well.

e. Traditionally, a sensitivity study consists of making several arbitrary perturbations in a single independent variable, or element performance map, and observing the effect of these perturbations on a dependent variable or figure-of-merit. In this example, the upper and lower levels of the uncertainty band were used rather than arbitrary perturbations which cannot be assessed.

f. It was felt that the uncertainty bands to be used in the sensitivity study should be established by the upper and lower levels of element performance which have been used in practice; i.e., the lower loss levels frequently used in the engine selection and design competitions and the higher levels of losses which have often been observed on the flight hardware. The upper and lower levels of the uncertainty band for exhaust system drag were established by considering:

(1) Historical data used in earlier airplane engine selection studies and the losses predicted by model tests.

(2) The maximum drag observed when flow separation occurs over a major portion of the afterbody due to steep closure or unfavorable interference (Figure 7).

The effect of exhaust system drag uncertainty on the engine cycle selection was examined by direct comparison of performance of the airplane with the lower level of afterbody drag (referred to as the "baseline" airplane), with performance of the airplane with the higher level of afterbody drag.

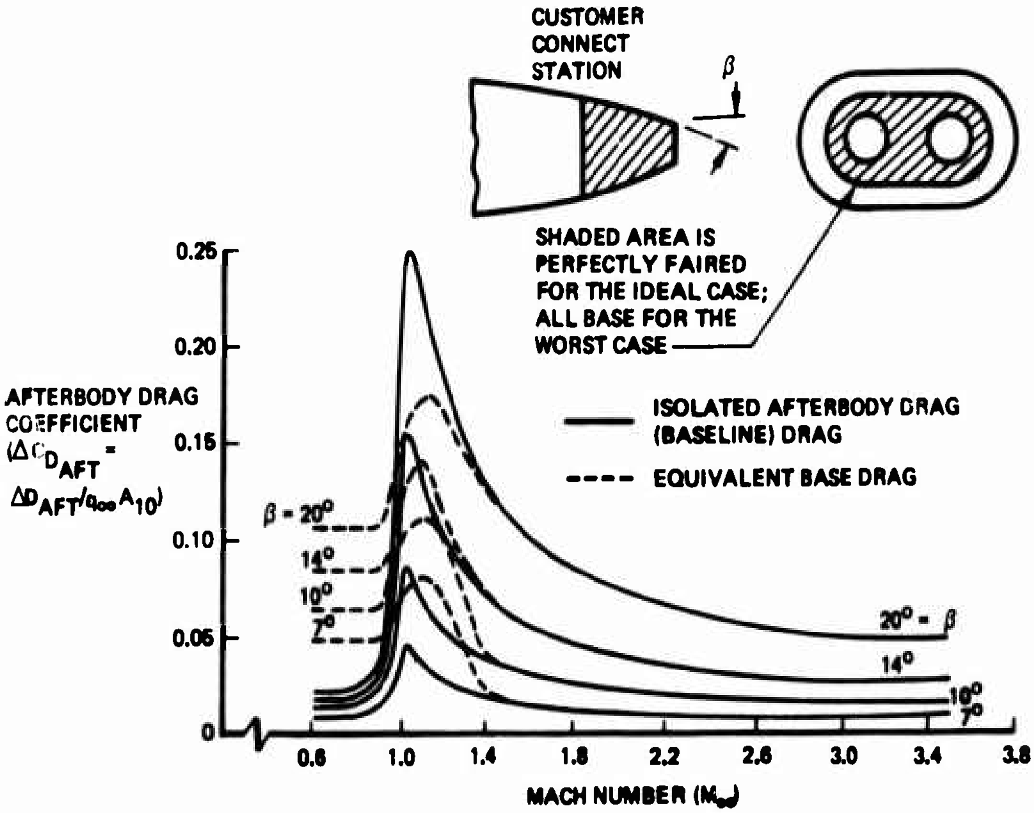


Figure 7. Afterbody Drag Uncertainty

g. Engine selection for the upper and lower levels of afterbody drag was accomplished with parametric perturbations in wing loading (W/S), and installed engine thrust-to-weight ratio (T/W). The airplane takeoff gross weight was held constant while subsonic and supersonic mission ranges were calculated. Airplane and propulsion system structural weight changes were calculated for all variations in W/S, T/W, and engine cycle. Since range was chosen as the figure-of-merit, all structural weight changes are reflected as changes in the available fuel capacity. A "thumbprint" plot of subsonic mission range decrement versus takeoff wing loading with the appropriate mission constraints superimposed, such as that shown in Figure 8, was constructed for each engine cycle and afterbody drag level.

The subsonic and supersonic range was calculated for the baseline airplane. The range requirements for the subsonic and supersonic missions were subtracted from these calculated values giving the range decrement. In these cases, all engine size and wing loading combinations resulted in ranges less than the design range requirements. This airplane, however, could have been scaled up in size to meet this mission requirement.

The effect of the uncertainty in exhaust system drag is summarized in Figure 9 where airplanes optimized with the maximum likely level of afterbody drag are compared with "baseline" airplanes which were optimized with the lower level of drag. It can be seen that for the low drag baseline airplane, both the subsonic and supersonic curves of range decrements are relatively flat across the range of bypass ratio from one to two. When the high drag level is assumed, the peak for the subsonic curve moves to lower bypass ratios and that for the supersonic curve moves toward higher bypass ratios. Equalization of range decrements requires a shift in bypass ratio towards lower values. Use of traditionally optimistic data may result in selection of a bypass two engine to gain a relatively small increment of 50 miles over the bypass one engine, whereas, if aft--end losses turn out to be significantly higher, bypass one would have been by far the better choice.

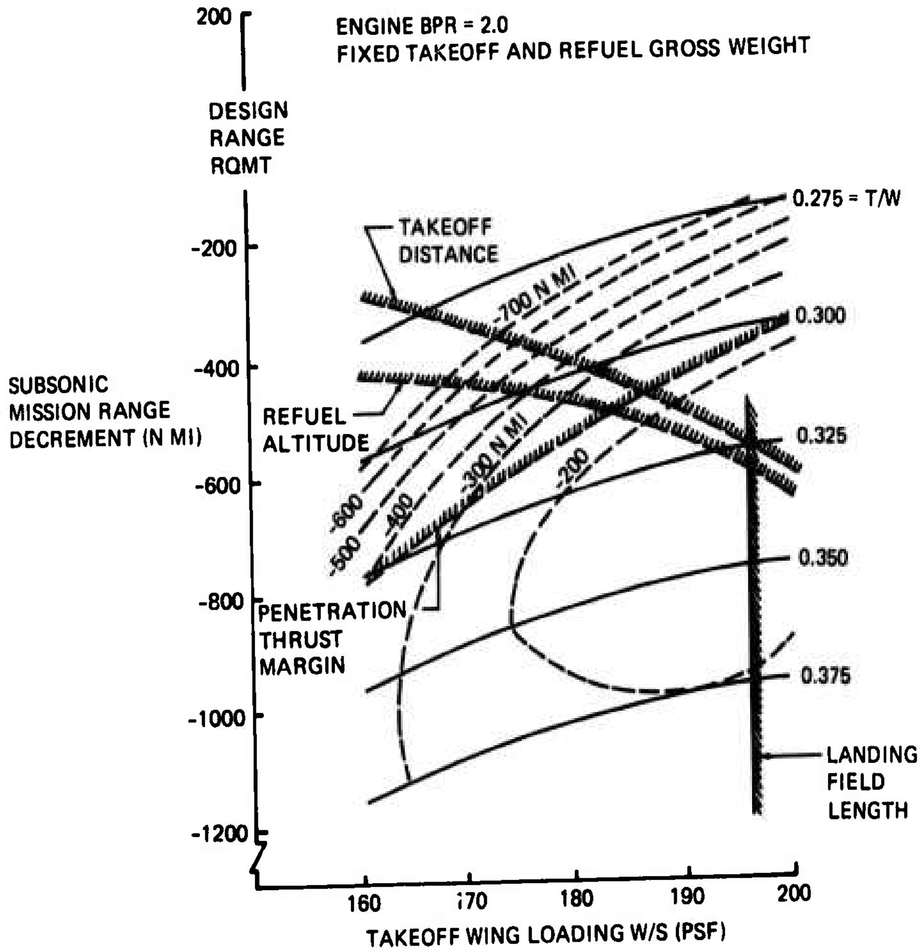


Figure 8. Airplane Thrust and Wing Loading Selection

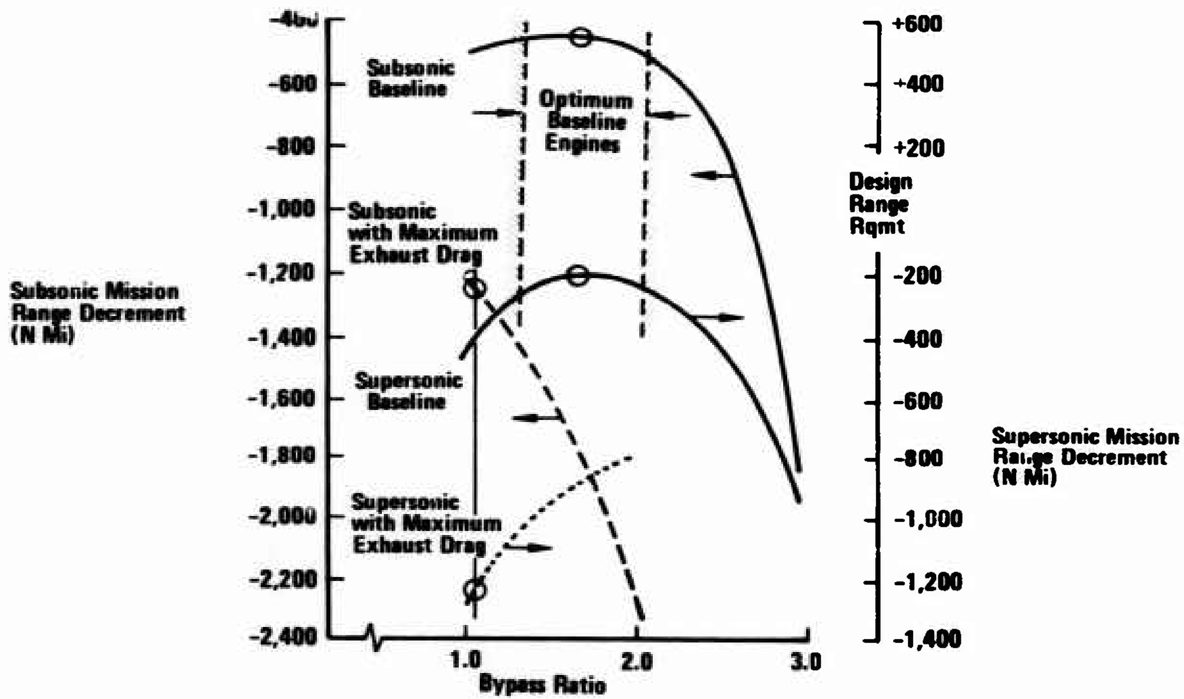


Figure 9. Influence of Afterbody Drag Uncertainty on Engine Cycle Selection

This example shows that a sensitivity analysis must be completed before engine cycle selection. The results of this sensitivity analysis and the uncertainty bands on propulsion system installation losses should both be considered to minimize the risk in engine cycle selection.

6.2 FLEXIBLE ENGINE CYCLES

System cost and system performance would be improved if something could be done to minimize the risk and impact of installation losses on cycle selection. One possible approach would be to provide another degree of flexibility in the engine to decrease the losses associated with a poor installation.

The reason for high installation losses can be traced to engine operating characteristics coupled with diverse mission requirements. The recent trend in military aircraft has been towards increasing thrust loading for improved maneuverability and supersonic performance as well as imposing stiff requirements for extended subsonic cruise range. Conventional engines designed to meet these requirements must operate over large ranges of airflow between maximum thrust and cruise thrust conditions; therefore, the achievement of an acceptable level of overall performance using conventional engines will become even more difficult.

For a conventional engine, thrust is reduced below intermediate power by reducing turbine inlet temperature. This reduces the work extraction rates of the turbine, which in turn reduces the compressor speed, pressure ratio, and engine airflow. In fact, at a typical subsonic cruise power setting, the engine demand may be only 60-70% of the design airflow. However, the inlet capture area must be sized to accommodate the maximum airflow that will be required in the flight envelope. As a result, at cruise power settings, substantial flow must be spilled or bypassed and high inlet drag results. The nozzle exit and throat areas must be large for the maximum afterburning condition, and at part power conditions the nozzle must be closed down to match the engine and to maintain acceptable levels of internal nozzle performance.

The closed-down nozzle tends to have a steep boattail angle and a large projected area, resulting in separated flow on the external surfaces and hence high aft-end drag.

It is apparent, therefore, that inlet and aft-end drags are related primarily to changes in airflow with thrust. An engine which can modulate thrust at constant airflow would not be required to spill inlet air nor to have steep boattail angles on a closed-down nozzle.

A recent study has shown that variable turbine geometry is a suitable mechanism within the engine for modulating thrust, holding airflow, and reducing installation drags.

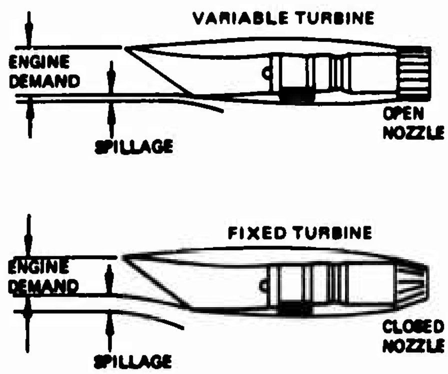


Figure 10. Comparison of Cruise Operating Characteristics

Figure 10 schematically shows the operational modes of conventional and flexible engines at typical subsonic cruise. When the flexible engine was operated in the unaugmented part power regime the turbine stator inlet temperature was reduced and the turbine geometry was varied to maintain turbine work extraction rate. This enabled the compressor airflow, pressure ratio, and speed to be held constant at design levels, and, in addition, increased the corrected flow entering the nozzle. The engine could, therefore, operate with a full flowing inlet and a wide open nozzle.

Considerable effort in recent years has been expended on engine cycles which come close to desired complete flexibility. These concepts range from relatively simple variable geometry components in conventional turbofans and turbojets to complex arrangements of airflow valves or groupings of turbofan and turbojet engines. All vary engine cycle and flow matching capability in some form and hence generally fall under the heading of variable cycle engines with the potential for reducing installation losses.

6.3 RISK CONSIDERATIONS

In all aircraft developments, installation loss sensitivity studies must be systematically completed throughout the various phases of the program. Several choice are then available for the proper selection of the engine cycle:

a. Select the optimum/least specific fuel consumption engine to obtain the highest possible vehicle performance. The program managers in this event must be prepared to accept program delays or cost overruns should their optimum not work out.

b. A better approach in most instances would be to opt for the least risk cycle based upon the sensitivity studies using realistic error bands prepared from studies of similar configurations.

c. The approach which appears to have the most potential for future systems is to utilize the flexibility of a variable cycle engine to reduce the impact on system performance of higher installation losses and changing mission requirements.

Choosing the latter approaches may involve a slight degradation of overall system weight, performance, and possibly some investment in technology programs. These factors should be weighed against the possibilities of cost overruns, schedule delays or unacceptable system performance should the optimum propulsion installation fall short of the expected performance goals.

SECTION VII

RECOMMENDED TIME PHASED DEVELOPMENT PROGRAMMING

This section describes a recommended concurrent engine-airframe development plan for the case when significant advances in the state-of-the-art in both engine and airframe are desired. Proper time phasing between engine and airframe work, such that the necessary information can be exchanged before critical decisions are made, results in a total program length of about 6-1/2 years, with about 1 year of intensive wind tunnel testing prior to the engine design and thrust freeze.

Such a long and expensive development period may not always be justified. It can be shortened considerably if existing airframe or engine hardware is used, less advancement in the state-of-the-art is accepted, a higher degree of risk is assumed, or the mission is simplified or kept flexible for acceptance of reasonable compromises between mission performance, cost, and development time. Even so, in all cases the whole program must be kept under constant review, and risks associated with major decisions must be evaluated. Each contractor should be aware of the progress and risks of the other's program at all stages. Proper evaluation of progress and risk can only be made if key information is constantly kept visible.

Most engine and airframe developments reach completion concurrently at the beginning of the aircraft flight test phase. Therefore, in preparing this development plan, the first step was to estimate total time spans required for individual elements. These are shown in Figure 11.

The development and testing schedule for the airframe is shown to be paced by airframe requirements only, and that for the engine by engine requirements only. An estimate of the uncertainty in drag or weight predictions is depicted as a function of time. When the schedules are simply aligned, the uncertainty in the drag and weight predictions at the time the cycle would be frozen is very high due primarily to the fact

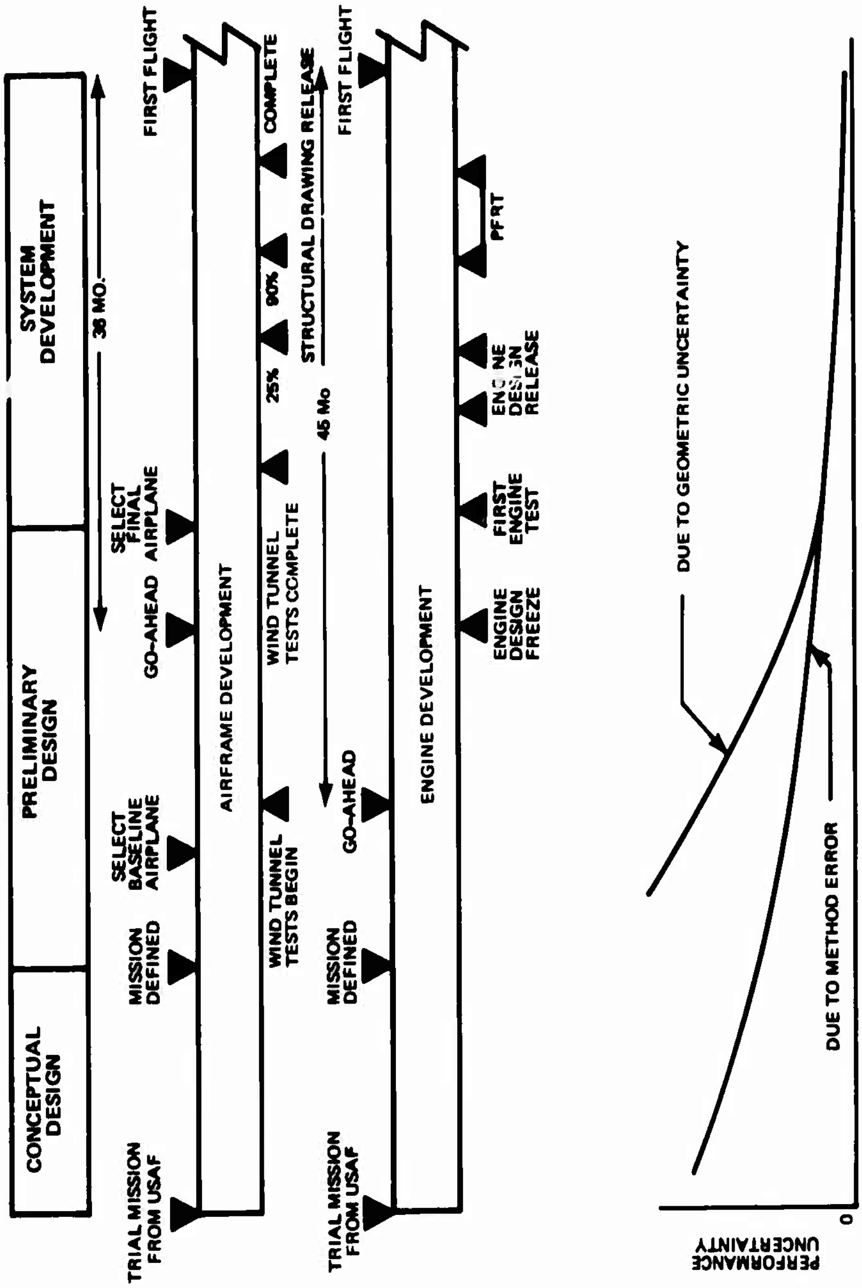


Figure 11. Current Time Phasing

that the configuration has not been fixed; the geometry is therefore uncertain, and little model testing has been completed. This is not a very satisfactory situation.

Our recommended plan is as follows. Since the weight and drag of the aircraft control the required thrust size and lapse rate, and since the engine cycle choice is strongly affected by installation losses, a recommended concurrent development plan has been prepared, as shown in Figure 12. The airplane schedule has been moved to the left relative to the engine schedule and then the Airframe Development Phase has been stretched to take advantage of the time required for engine development.

The cycle freeze has been set near the completion of the Preliminary Design Phase. At this time, all aft-end testing and about half of the inlet and airframe testing have been completed. The thrust freeze would then occur six months later. At this time the final airplane configuration has been selected and the geometric uncertainties have been eliminated. Very little improvement in drag and weight prediction uncertainties can be expected after that date. However, a sizable uncertainty still remains.

Any uncertainty in the predicted performance and weight of each major element of the airplane must be considered in future development programs. Cycle and thrust freezes must be preceded by an analysis of the consequences of a positive or negative error in predicted performance. In this way, we can make a prudent trade of risk versus airplane performance or cost and choose the cycle and later the thrust size accordingly.

A similar reassessment should be conducted around the 90% drawing release date, when weight prediction errors should be reduced to a minimum.

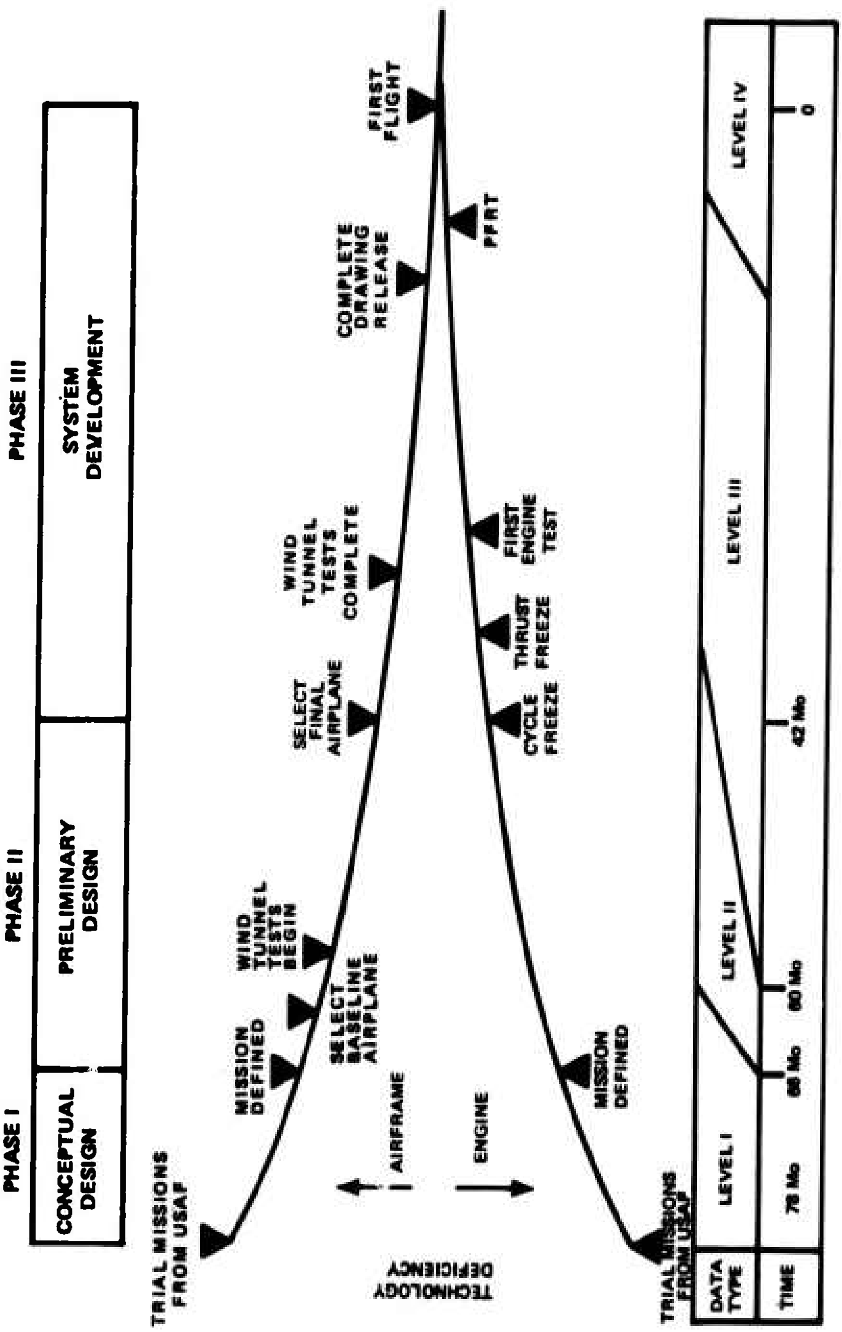


Figure 12. Recommended Time Phasing

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

Present methods of predicting airplane element performance from empirical model data and analytical methods are not sufficiently accurate to be used as a base for selecting the engine cycle. A number of aircraft systems have failed to fully achieve design performance primarily because the propulsion system performance failed to meet requirements. This document reviews the various facets of engine cycle selection including the time phasing between airframe and engine development programs, thrust/drag accounting systems, and recognizing and minimizing risks in engine cycle selection. This review has resulted in the following recommendations:

a. Analysis used in system performance estimations should be treated as uncertain at all times in a development program. The extent of the uncertainty should be based upon the technology level, the supporting data, experience, firmness of the design configuration, etc.

b. Data used in system performance estimation should similarly be treated as uncertain at all times. The degree of uncertainty will decrease through the program as testing is completed and the configuration lines evolve.

c. Thrust/drag accounting methods should generally be applicable throughout the development. The thrust/drag system should be based on three criteria. First, and most important, is the requirement for accuracy in predicting the overall thrust-minus-drag performance. Secondly, the performance integration procedures should provide meaningful performance visibility for the airplane system elements. Finally, the system should be applicable with consistent definitions throughout an entire airplane development program.

d. Continuous and free exchange of all data is required between airframe and engine contractors.

e. An integrated time phased engine/airplane development program is necessary for proper decision making. The timing of the engine selection must insure adequate engine development time but must have as its foundation adequate test data acquired from a firm definition of the airplane configuration.

f. Model test techniques should include an aero force and moment model, a jet effects model, and an inlet model. In addition, testing should investigate the following: support effects, splitline location, mass flow effects, scale effects, Reynolds number effects, trim effects, and blockage effects.

g. Sensitivity studies should be completed in all phases of the development program using realistic uncertainty bands on the data. Early studies should determine which elements are strongly affecting airplane performance and so indicate the test and design priorities required.

h. The risk of error in cycle selection should be minimized by accepting penalties relative to the "optimum" solution to a degree which the sensitivity study indicates is prudent.

i. If possible, and particularly if the vehicle is sensitive to installation losses, flexibility in engine cycle should be maintained into the flight test stage by selection of a variable cycle engine. This will not only reduce the risk of wrong cycle selection but will lessen the impact of changing mission requirements during the long development span and life of most major weapon systems.

The political atmosphere currently leans towards minimizing the costs of aircraft developments. A necessary approach for cost-effective future aircraft developments is for both the government and industry to actively pursue proper methodology for engine cycle selection; this should then lessen the possibilities of major cost escalations, crash technology

programs, or degradation of mission capability. The key to correct engine cycle selection lies in the realistic evaluation and proper accounting of installation losses.

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